Software Defined GPS Receiver for International Space Station

Courtney B. Duncan
David E. Robison
Cynthia Lee Koelewyn
all of
Jet Propulsion Laboratory,
California Institute of Technology

BIOGRAPHIES

Courtney Duncan holds an MSEE in Communications Systems from the University of Southern California, a BSEE with Honors from the University of Houston, and a BM from Baylor University and has been involved in flight and ground software and hardware for numerous space missions. He was System Engineer for the Gravity Processor Assembly on the GRAIL lunar gravity mission; contributor to MONTE, JPL's multi-mission deep space navigation software; Software Manager for the Micro Arcsecond Metrology test bed of the Space Interferometry Mission; Instrument Manager for the Black Jack GPS Receivers flown on the Shuttle Radar Topography Mission (SRTM, STS-99); contributor of real-time, embedded software to determine orbit, time, and coarse attitude and to autonomously schedule GPS atmospheric sounding science observations on GPS-MET, an instrument on the Orbital Sciences MicroLab-1; and was worldwide ground control and communications network manager for four early micro-satellites, including AMSAT-OSCAR-16, launched in January 1990, which were direct ancestors of today's university CubeSats. He currently serves as Task Manager for GPS Waveforms for CoNNeCT, L1, L2 & L5.

David Robison holds a BS and MEng in Electrical Engineering and Computer Science from MIT, and has worked in the Advanced Radiometric and Gravity-Sensing Instruments group at JPL since 2001. He has served as the Cognizant Engineer for GPS Receiver instruments on COSMIC, OSTM, and UAV-SAR. His varied contributions include the in-flight firmware upgrade that enabled L2 Civil tracking on CHAMP and COSMIC, as well as the data processing firmware for the Moon Mineralogy Mapper. He is currently responsible for signal processing firmware design for the TriG GNSS Receiver and the CoNNeCT GPS Waveform.

Cynthia Koelewyn holds a BS in Electrical and Computer Engineering Technology from California Polytechnic University, Pomona and a MSEE in Electrical Engineering from California State University, Northridge. She has been involved in development of flight hardware for several space missions; was a test engineer for the Payload Global Positioning System Receiver for OSTM; currently serves as the Cognizant Engineer for the Global Positioning System Module for the CoNNeCT SDR; and is Avionics System Engineer for MSL.

ABSTRACT

JPL is providing a software defined radio (SDR) that will fly on the International Space Station (ISS) as part of the CoNNeCT project under NASA's SCaN program. The SDR consists of several modules including a Baseband Processor Module (BPM) and a GPS Module (GPSM). The BPM executes applications (waveforms) consisting of software components for the embedded SPARC processor and logic for two Virtex II Field Programmable Gate Arrays (FPGAs) that operate on data received from the GPSM. GPS waveforms on the SDR are enabled by an L-Band antenna, low noise amplifier (LNA), and the GPSM that performs quadrature downconversion at L1, L2, and L5. The GPS waveform for the JPL SDR will acquire and track L1 C/A, L2C, and L5 GPS signals from a CoNNeCT platform on ISS, providing the best GPS-based positioning of ISS achieved to date, the first use of multiple frequency GPS on ISS, and potentially the first L5 signal tracking from space. The system will also enable various radiometric investigations on ISS such as local multipath or ISS dynamic behavior characterization. In following the software-defined model, this work will create a highly portable GPS software and firmware package that can be adapted to another platform with the necessary processor and FPGA capability. This paper also describes ISS applications for the JPL CoNNeCT SDR GPS waveform, possibilities for future global navigation satellite system (GNSS) tracking

development, and the applicability of the waveform components to other space navigation applications.

INTRODUCTION

NASA plans to fly the JPL CoNNeCT SDR to ISS in 2012. The SDR is an element of the Communications, Navigation, and Networking reConfigurable Testbed (CoNNeCT) project under NASA's SCaN (Space Communication and Navigation) technology development program. The CoNNeCT project, consisting of both flight and ground systems, provides a platform for demonstrating new space communication and navigation systems relevant to future NASA missions. The CoNNeCT project also introduces the Space Telecommunications Radio Systems (STRS) specification for software architecture for implementations on CoNNeCT SDRs. This paper describes work at JPL to develop a GPS Receiver application for the JPL SDR.

The CoNNeCT flight system will be integrated with an experiments package, launched to the ISS on JAXA HTV-3 in January 2012, and installed robotically. The location of the package on ISS is shown in Figure 1.
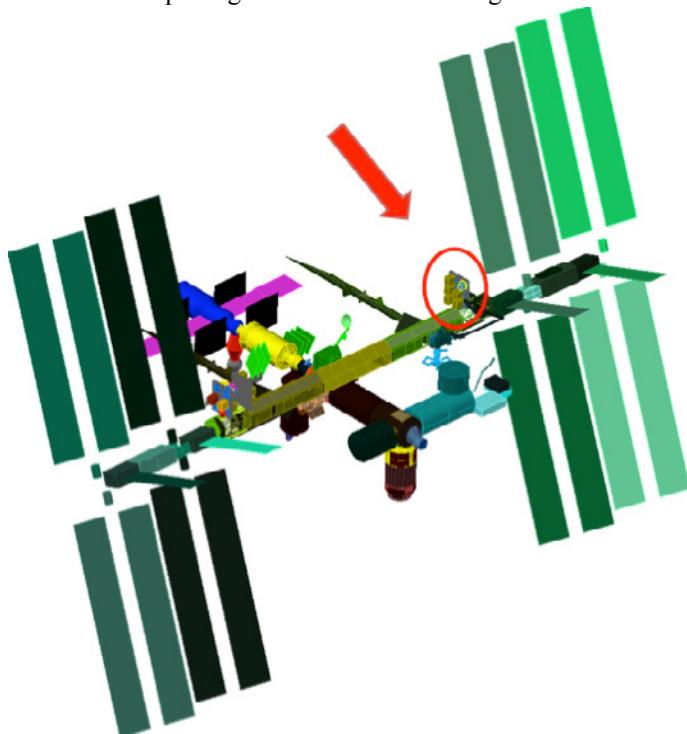

Figure 1. Location of CoNNeCT on ISS.

The JPL SDR is one of three SDRs under development for CoNNeCT, the others being provided by General Dynamics and Harris. The CoNNeCT SDRs are reconfigurable, allowing in flight uploads of new application-specific executables. Build packages containing executables for on-board microprocessors and FPGAs are referred to as "waveforms."

The JPL SDR assembly consists of a Radio Frequency Module (RFM), a Baseband Processor Module (BPM), a Global Positioning System Module (GPSM), and a combined Solid State Power Amplifier/Power Supply Module (SSPA, PSM), shown in Figure 2.
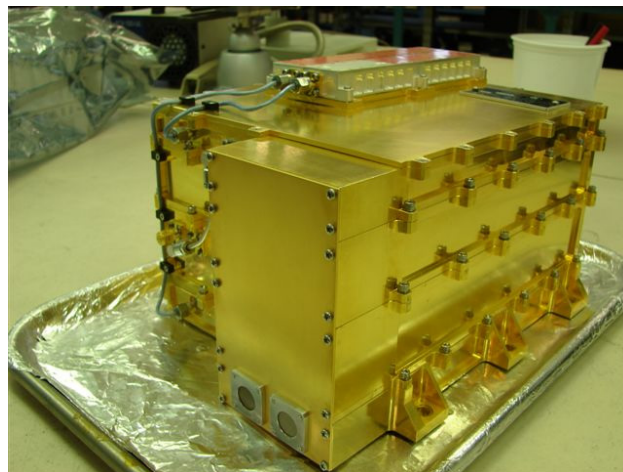

Figure 2. JPL SDR

The BPM features a SPARC processor and two Virtex II FPGAs for use by waveform applications.

The GPSM down-converts and samples the L-Band GPS signals at three frequencies (L1, L2, and L5). Together with an L-band antenna and LNA, the GPSM enables GPS waveforms on the JPL SDR.

To support waveform development, JPL has developed a POSIX-compliant Operating Environment (OE) based on the STRS specification that defines standards for software and FPGA interfaces and provides basic infrastructure for generating CoNNeCT waveforms. The underlying operating system (OS) is RTEMS. Development is supported in C and C++ for the SPARC and in Verilog and VHDL for the Virtex FPGAs.

In flight, CoNNeCT will be operated from the ground via TDRSS, independent from ISS crew activity (Figure 3). The JPL SDR supports in-flight upload of new waveforms to a bank of non-volatile on-board memory. Any waveform stored on the SDR can then be individually loaded and run. The GPS Waveform currently under development will, when executed on the JPL SDR, autonomously acquire and track GPS signals, calculate ISS position, and transmit observable data to the CoNNeCT data handler for downlink via TDRSS.
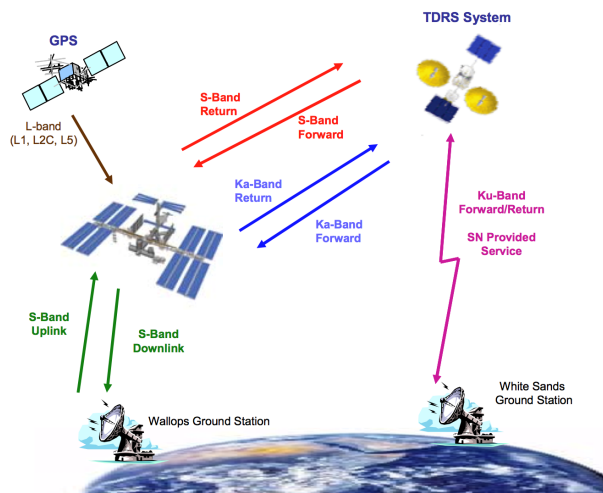
Figure 3. GPS Waveform Operation on CoNNeCT.

The team developing the CoNNeCT GPS Waveform has developed software for science-grade GPS receivers for ground and flight for several years and has a substantial base of legacy software that performs many of the functions to be implemented. Much of this legacy code is being ported during to the GPS Waveform. Also, much of the logic being developed for the FPGA derives from a prior implementation in ASIC.

GPS WAVEFORM

The GPS signal is received through a Dorne & Margolin DMC146-6-1 passive antenna with choke rings (Figure 4) and amplified prior to the GPSM (Figure 5). The GPSM then performs down-conversion and one bit analog-to-digital conversion for each of the three GPS frequency bands: L1, L2, and L5.
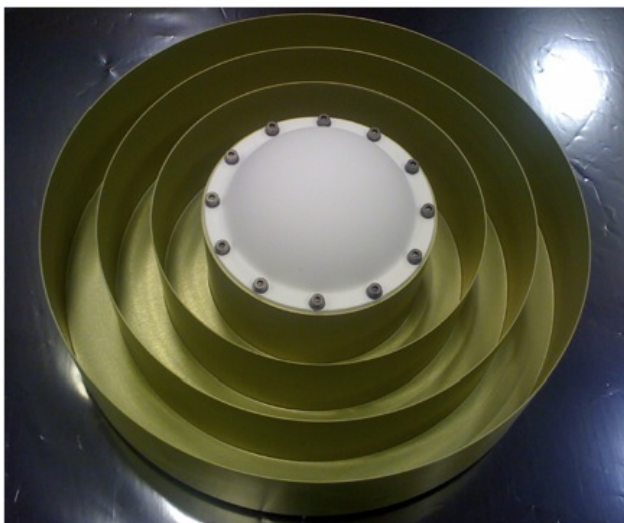

Figure 4. CoNNeCT GPS Antenna.

The GPSM utilizes a sub-harmonic sampling technique, as implemented on receivers for COSMIC, GRACE, GRAIL (S-Band crosslink), and other missions *[Thomas, 1995]*. The design is adapted here to include the L5 frequency in addition to L1 and L2.
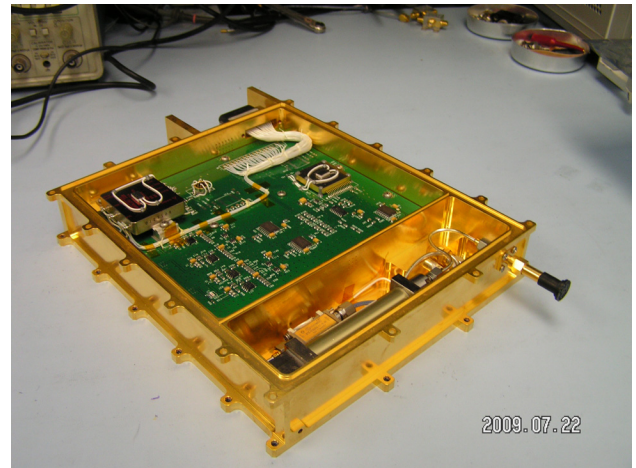

Figure 5. JPL CoNNeCT GPSM.

The basic operation of the GPS Waveform is to process digital samples of the L1, L2, and L5 spectra produced by the GPSM into pseudoranges that are then used to calculate an estimate for GPS time, position, and velocity at the L-band antenna. The waveform will be capable of tracking L1 C/A, L2C, and L5, but will not include L1P or L2P codeless tracking.

To reduce time to first fix (TTFF) and minimize load on both processor and FPGA resources, initial acquisition is performed on the L1 C/A in the frequency domain, using Fast Fourier Transforms (FFTs). L1 C/A tracking is then used to perform aided acquisition on L2C and L5 signals.

Code delay (pseudorange) and carrier phase are tracked for each signal with an FPGA-based feedback loop at 50 Hz, aided by software-based corrections at 1 Hz. The pseudorange and carrier phase models together with the corresponding residual errors are used to form raw observables and navigation solutions at 10-second intervals.

The navigation algorithm computes GPS satellite positions and clock parameters from the broadcast ephemerides received via the data bits modulated on the tracked signal then solves simultaneously for the antenna position and receiver clock from its ranging observations using a standard least squares fitting technique.

SDR APPROACH TO NAVIGATION

Although software GNSS receivers are commonly used for research applications, most GNSS receiver

architectures rely on custom signal processing ASICs. In adopting the software receiver model, the CoNNeCT GPS waveform represents a new paradigm for space GNSS receivers: in place of a dedicated instrument, the receiver function is hosted as an application on system resources, requiring only the addition of an L-band front end, the GPSM *[Reinhart, et al, 2010]*.

While dedicated hardware has traditionally held a strong advantage in size, weight and power, advances in processor and FPGA technology make the software approach a viable alternative for spaceborne applications.. There are several advantages and applications of such an approach. A software GNSS receiver creates the potential for greater system efficiencies through resource sharing.

For smaller satellites, where power and mass are tightly constrained a software GNSS receiver can share processing resources with other functions, requiring minimal dedicated hardware. For science applications, such as radio occultation and GNSS reflections, experiments can be run in the background on system or communication resources, enabled whenever processing assets are available. For deep space or lunar missions, a navigation instrument implemented as a software receiver can reconfigure for each phase of the mission, e.g. a GNSS receiver for the near earth phase, a Doppler-based navigation receiver during cruise, and a custom in-situ navigation or gravity recovery instrument once the destination is reached.

Software navigation receivers also hold an advantage in their capability for in-flight upgrades. With numerous new GNSS systems, satellites, and signals projected to come online over the next several years (such as Galileo E1 and E5a), a software receiver in space can be reconfigured over time to efficiently match changes in the GNSS constellations. Experimental GNSS applications, where incremental improvements or adjustments may be needed to enhance science return, will also benefit from the software receiver approach.

The flexibility of the SDR also allows for experimentation with advanced tracking scenarios that would not be available on a standard transponder, such as very low SNR tracking of GPS signals from the moon.

The JPL BlackJack GPS receiver can be taken as a case study on the advantages of a software-defined approach. While not fully reconfigurable (the BlackJack includes JPL's TurboRogue ASIC for GPS signal processing), it implements the majority of functions in software, and includes an FPGA that can be used for custom signal processing implementations. The configurable architecture has allowed the design to be upgraded in flight, including an upgrade to the CHAMP and COSMIC receivers that added L2C capability *[Citation to be*

added]. The BlackJack receiver was also adapted to custom radiometric applications, including GRACE, for which the BlackJack receiver implemented a microwave crosslink for dual one-way range in addition to GPS; and GRAIL, for which the receiver implemented an S-band time transfer link in place of GPS. For GRACE and GRAIL, the new functions were accomplished with only minimal changes to the digital hardware; the majority of changes were in RF hardware. Software updates were required, but those were also minimal: source code modifications between the GRACE and GRAIL missions were less than 3 percent by line count *[Citation to be added – Rogstad]*. It is anticipated that the JPL SDR implemented on CoNNeCT will have even greater adaptability, since no custom signal processing ASICs are included. The potential applications are limited only by processing power (processor MIPs, FPGA resources) and the available RF hardware.

EXPECTED PERFORMANCE

The single-bit sampling technique used here has produced code pseudorange precision of 1 – 2 nanoseconds (0.3 – 0.6 meters) at nominal SNRv of 500 (normalized to one second). Carrier phase tracking precision is a few tens of picoseconds (a few millimeters). *[Citation to be added - GRAIL]* In GNSS applications, errors introduced by multipath and media delays always dominate thermal noise in tracking observables *[Citation to be added – ancient Rogue or TurboRogue]*. In post processing, multipath signatures are mitigated, media are removed or estimated, pseudorange precision is improved to phase precision levels, and improved GPS satellite ephemerides are used to produce position solutions accurate to a few centimeters. *[Citation to be added - GIPSY]*

The CoNNeCT GPS Waveform will rely primarily on pseudorange measurements and will compute positions onboard with an accuracy of several meters (ten meters required), an improvement over the current ISS GPS implementation *[Gomez, 2005]*. Calibration of ionosphere effects will be performed on measurements from satellites transmitting L2C modulation and/or L5 signals but carrier phase will not be used onboard or in post processing in the first delivery of this waveform. Improved GPS ephemerides in post processing will improve the position solutions to a few meters accuracy.

The waveform will track all L1 signals in view to the CoNNeCT zenith-looking hemispherical coverage antenna (10-12 expected) and all available L2C and L5 available from among those. (Only recently launched GPS satellite transmit the new L2C and L5 signals.)

FUTURE WORK

The GPS Waveform for CoNNeCT will demonstrate GPS functionality and performance on the JPL SDR. Beyond the initial demonstration, the waveform will also facilitate further research and experimentation. The configurable SDR architecture enables incremental modification, and allows data to be captured from any stage in the digital signal processing, whether raw digital samples or accumulator outputs or pseudorange observables. This flexibility serves as a powerful tool for in-orbit experiments. Anticipated work based on the JPL SDR and the GPS waveform will include: precision timing, expansion to include new GNSS signals and constellations, advanced acquisition and tracking techniques, incorporation of external corrections, such as from the TDRSS Augmentation Service for Satellites (TASS) *[Dorsey, et al, 2009]*, measurement of GNSS occultations and reflections, and implementation of radiometric tracking functions such as range and Doppler measurements used in navigation of interplanetary spacecraft.

The ISS represents a challenging environment for precise orbit determination, when compared to a typical LEO satellite. Multipath and structural dynamics are significant concerns. GPS waveforms on CoNNeCT will be used to characterize the local multipath environment, and evaluate mitigation strategies. The waveform will also be used to determine the effects of structural dynamics on orbit determination and evaluate the stability of the ISS truss, providing relevant data for future use of the ISS as an experiment platform.

CONCLUSIONS

JPL's CoNNeCT SDR and GPS Waveform will provide position information for ISS with improved accuracy and will enable a multitude of follow-on investigations, both of ISS conditions and phenomena visible from ISS.

The SDR will be launched to ISS and become operational in 2012. The GPS Waveform now under development will be uploaded to the JPL SDR on ISS after CoNNeCT installation.

Software radio technology allows the platform and the tracking and navigation techniques used to be more flexible and experimental in nature than is possible with single-purpose dedicated equipment.

ACRONYMS

BPM   Baseband Processor Module

C/A   Coarse / Acquisition

CoNNeCT   Communications, Navigation, and Networking reConfigurable Testbed

COSMIC   Constellation Observing System for Meterology, Ionosphere and Climate

FFT   Fast Fourier Transform

FPGA   Field Programmable Gate Array

GNSS   Global Navigation Satellite System

GPS   Global Positioning System

GPSM   Global Positioning System Module

GRACE   Gravity Recovery and Climate Experiment

GRAIL   Gravity Recovery and Interior Laboratory

IFFT   Inverse Fast Fourier Transform

IAIN   International Association of Institutes of Navigation

ISS   International Space Station

JPL   Jet Propulsion Laboratory

L1   1.57542 GHz

L2   1.27760 GHz

L5   1.17645 GHz

LEO   Low Earth Orbit

LNA   Low Noise Amplifier

NASA   National Aeronautics and Space Administration

OE   Operating Environment

OS   Operating System

POSIX   Portable Operating System Interface for UniX

PRN   Pseudo Random Number

PSM   Power Supply Module

RFM   Radio Frequency Module

RTEMS Real Time Executive for Multiprocessor Systems

SCaN   Space Communications and Navigation

SDR   Software Defined Radio

SNRv   Signal to Noise Ratio in Voltage

SPARC Scalable Processor Architecture

SSPA   Solid State Power Amplifier

STRS   Space Telecommunications Radio System

TASS   TDRSS Augmentation Service for Satellites

TDRSS Tracking and Data Relay Satellite System

TTFF   Time To First Fix

VHDL   VHSIC Hardware Definition Language

VHSIC Very High Speed Integrated Circuit

XOR   Exclusive Or logic operation

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